EFFECT OF PAVEMENT CONDITIONS ON FUEL CONSUMPTION, TIRE WEAR AND REPAIR AND MAINTENANCE COSTS

Graduate of Polytechnic School of Tunisia, 2004. Completed a master degree in 2005 in applied math to computer science, M.S. and Ph.D. degrees in Pavement engineering from Michigan State University, USA, in 2008 and 2010. Currently she is a Research Associate at the civil and environmental engineering department at MSU.
Email: zaabarim@egr.msu.edu

Imen ZAABAR
Michigan State University
USA

Obtained B.S. and M.S. from Michigan State University, USA, in 1985 and 1987 and a Ph.D. degree in Pavement Engineering from the University of California-Berkeley in 1992. Joined the civil and environmental engineering department at MSU in 1993 where he is currently a Professor.
Email: chatti@egr.msu.edu

Karim CHATTI
Michigan State University
USA

Abstract

This paper presents a summary of findings on the effect of pavement conditions on fuel consumption (FC), repair and maintenance (R&M) and tire wear (TW) costs. An increase in IRI of 1 m/km increases FC of passenger cars (PC) by 2% irrespective of speed. For heavy trucks (HT), this increase is 1% at highway speed (96 km/h) and 2% at low speed (56 km/h). Surface texture (MPD) and pavement type have no effect on FC for all vehicle classes except for HT. An increase in MPD of 1 mm increases FC by 1.5% at 88 km/h and 2% at 56 km/h. HT driven on AC pavements consume 4% more fuel than on PCC pavements at 56 km/h in summer conditions. The effect of pavement type was statistically not significant at higher speeds. No data was available for HT in winter. For R&M, there is no effect of roughness up to IRI of 3 m/km. Beyond this range, an increase in IRI up to 4 m/km increases R&M cost by 10% for PC and HT. At IRI of 5 m/km, this increase is up to 40% for PC and 50% for HT. An increase in IRI of 1 m/km increases TW of PC and HT by 1% at 88 km/h.

Keywords: Vehicle Operating Costs, Fuel consumption, Tire Wear, Repair and Maintenance Costs, Pavement Conditions.

1. Introduction

This paper presents a summary of findings from the research conducted under project NCHRP 1-45, whose objective was to recommend models for estimating the effect of pavement conditions on Vehicle Operating Costs (VOC). The recommended models reflect current vehicle technologies in the United States. The research focused only on the cost components that are mostly affected by pavement conditions, namely fuel consumption, repair and maintenance costs and tire wear. The research does not include the effect of pavement conditions on changes in travel time, nor does it consider the safety-related or other implications of pavement conditions.

First, a large amount of data and information was collected, reviewed and analyzed to identify the most relevant VOC models. The review was focused on research that has identified factors affecting VOC costs including pavement conditions. Next, a large field investigation involving surveys to collect pavement condition data and field trials to collect fuel consumption and tire wear data were conducted. These data were used to calibrate and validate the HDM 4 fuel consumption and tire wear models for conditions in the US and estimate the effect of pavement conditions on these components. The research also involved the collection of the repair and maintenance data of vehicle fleets from two DOTs (Michigan and Texas). The fleet data were used to update the TRDF approach and develop a mechanistic-empirical repair and maintenance models that consider the paved surface conditions encountered in the United States and address the full range of vehicle types. The paper begins with a summary of findings from the research. This is followed by case studies and results from the application of the mechanistic-empirical models recommended in this research. Table 1 summarizes the units costs used in this study.

Table 1 – Unit Costs

Vehicle class	Fuel Cost † ($/gallon)	Fuel Cost† ($/liter)	Tire Cost† ($/tire)	Repair and maintenance costs ($/mile)*	Repair and maintenance costs ($/km)*
Small car	$3.63	$0.96	$100	0.064	0.040
Medium car	$3.63	$0.96	$100	0.064	0.040
Large car	$3.63	$0.96	$100	0.064	0.040
Van	$3.63	$0.96	$150	0.083	0.052
Four wheel drive	$3.63	$0.96	$150	0.083	0.052
Light truck	$3.63	$0.96	$175	0.083	0.052
Medium truck	$3.63	$0.96	$200	0.092	0.058
Heavy truck	$3.97	$1.05	$250	0.119	0.074
Articulated truck	$3.97	$1.05	$250	0.191	0.119
Mini bus	$3.63	$0.96	$150	0.199	0.124
Light bus	$3.63	$0.96	$175	0.083	0.052
Medium bus	$3.97	$1.05	$200	0.092	0.058
Heavy bus	$3.97	$1.05	$250	0.119	0.074
Coach	$3.97	$1.05	$250	0.191	0.119

*These costs are repair and maintenance estimated based on data from 2007.

†These costs are estimates for 2011.

2. Fuel Consumption

2.1 Summary of findings

The effect of pavement conditions was investigated using five instrumented vehicles to measure fuel consumption over different pavement sections with different pavement conditions. This data was used to calibrate the HDM 4 fuel consumption model. The calibrated models were verified and were found to adequately predict the fuel consumption under different operating, weather, and pavement conditions (Zaabar and Chatti, 2010). Figure 1 presents the fuel consumption as a function of IRI for all vehicle classes. The figure was generated at 17˚C (62.6˚F) when the mean profile depth is 1 mm (0.04 in) and grade is 0%.

The analysis assumed that there is no interaction between the effect of roughness (unevenness) and surface texture given that their wavelength ranges are independent. The model showed pavement surface texture has an effect on fuel consumption only for heavier trucks. For example, a 1 mm decrease in mean profile depth will result in decrease in fuel consumption of 2.25 % and 1.5 % at 56 and 88 km/h (35 and 55 mph) speeds, respectively.

The analysis showed that there is no interaction between the effect of roughness and pavement type. The analysis also showed that the difference in fuel consumption between asphalt and concrete pavements could only be detected at low speed and for heavy and fully loaded light trucks in summer conditions (Zaabar and Chatti, 2011). Heavy trucks driven over AC pavements will consume about 4% more fuel than over PCC pavement at 56 km/h (35mph) in summer conditions. The effect of pavement type was statistically not significant at higher speeds. No data was available for heavy trucks in winter.

2.2 Discussion

Reduction in vehicle fuel consumption is one of the main benefits that should be considered in technical and economic evaluations of road improvements considering its significance. This research showed that a decrease in pavement roughness by 1 m/km (63.4 in/mile) will result in a 3 percent decrease in the fuel consumption for passenger cars. This would save about 6 billion gallons of fuel per year of the 200 billion gallons consumed annually by the 255 million vehicles in the United States. With today’s gas prices, this will translate to about 24 billion dollars.

3. Tire Wear

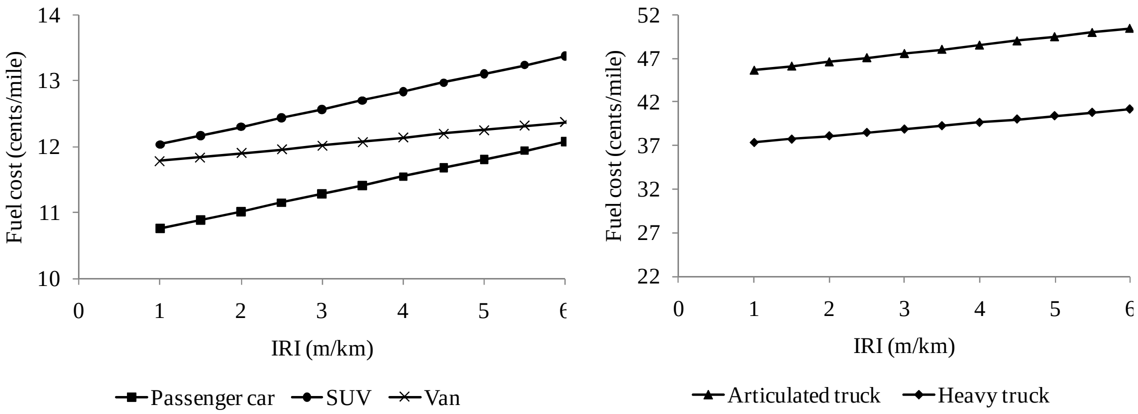
3.1 Summary of findings

The effect of pavement conditions on tire wear was investigated in this research using field data. The HDM4 tire wear model was calibrated, and adequately predicted the tire wear of passenger cars and articulated trucks.

Figure 2 presents the tire wear as a function of IRI for all vehicle classes at 56, 88 and 112 km/h (35, 55 and 70 mph). The figure was generated at 17˚C (62.6˚F) when the mean profile depth is 1 mm (0.04 in) and grade is 0%. These data show, for the same IRI value, that tire wear increases with increasing speed, and that the roughness effect is higher at higher speeds.

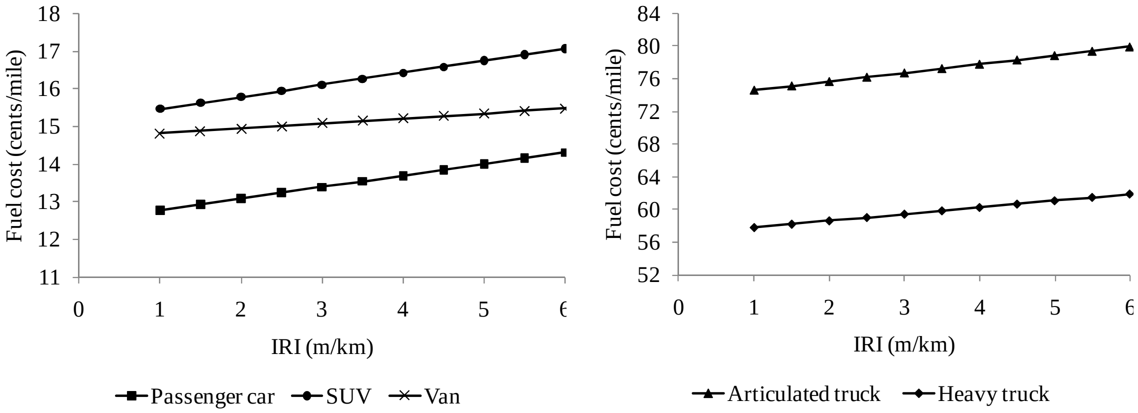
3.2 Discussion

This research showed that a decrease in pavement roughness by 1 m/km (63.4 in/mile) will result in about 1 percent decrease in the tire wear for passenger cars. Assuming that the average annual kilometrage (mileage) for a passenger car is 24000 km (15,000 miles) and the average price of a tire is $100, the 255 million vehicles will consume about 32.1 billion dollars per year. Therefore, a decrease in IRI by 1 m/km (63.4 in/mile) will save 321 million dollars per year.



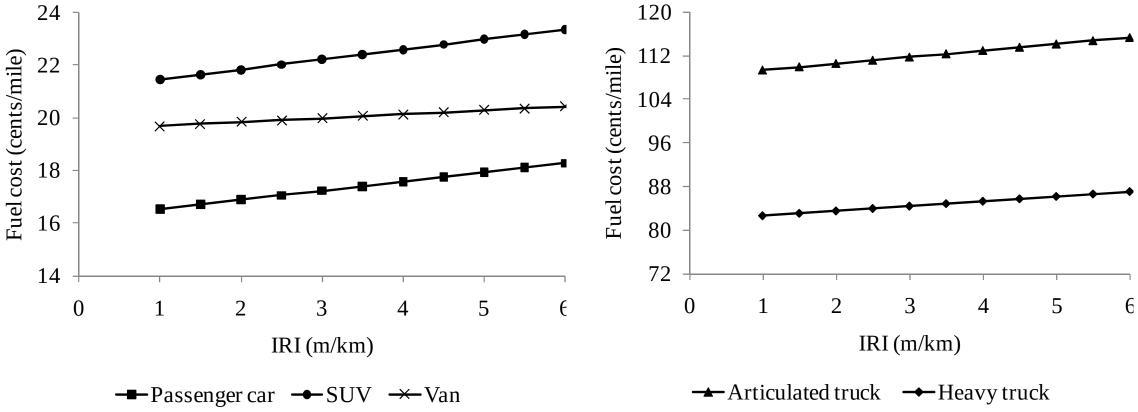
(a) Light vehicles at 56 km/h (35 mph)

(b) Trucks at 56 km/h (35 mph)



(c) Light vehicles at 88 km/h (55 mph)

(d) Trucks at 88 km/h (55 mph)

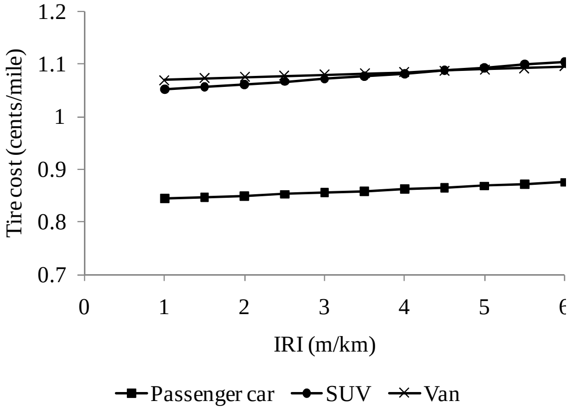


(e) Light vehicles at 112 km/h (70 mph)

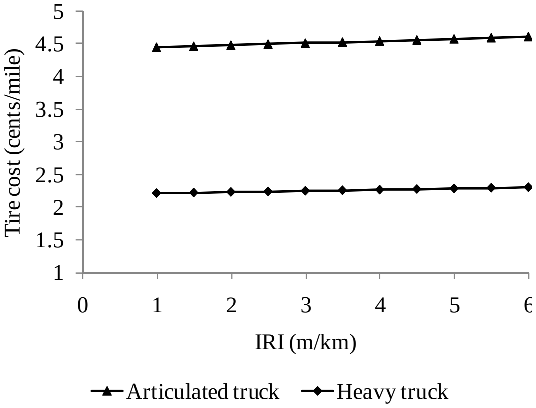
(f) Trucks at 112 km/h (70 mph)

■ Passenger car ● SUV × Van ▲ Articulated truck ◆ Heavy truck

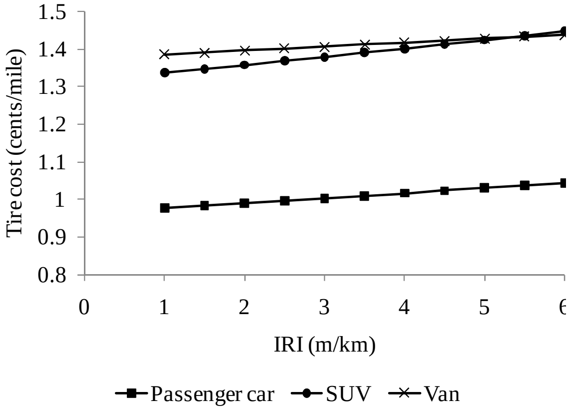
Figure 1– Effect of roughness on fuel costs



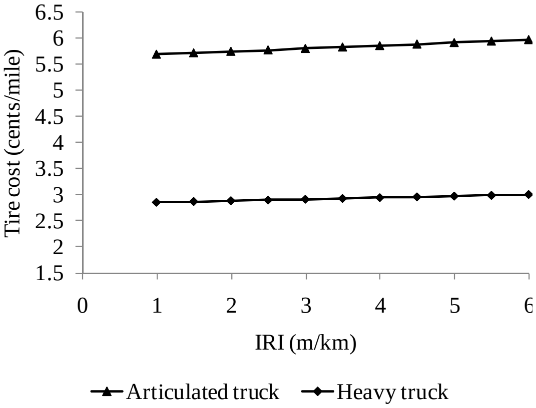
(a) Light vehicles at 56 km/h (35 mph)



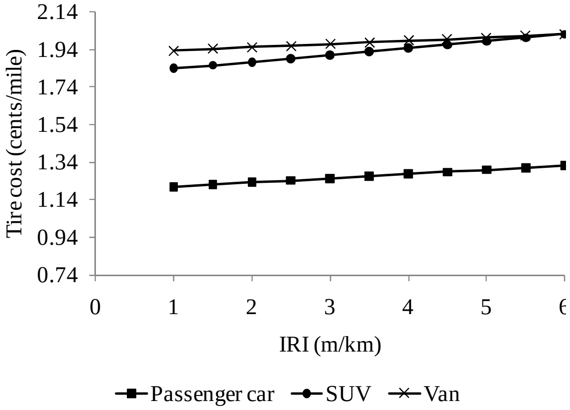
(b) Trucks at 56 km/h (35 mph)



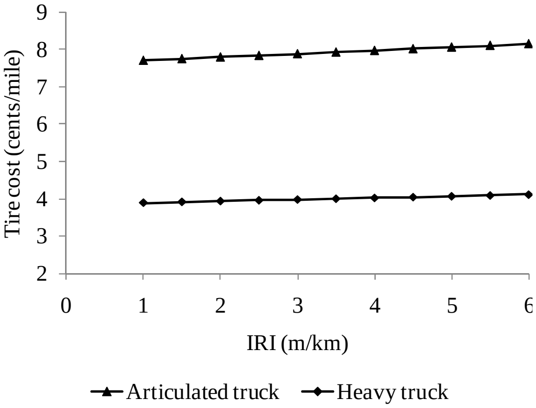
(c) Light vehicles at 88 km/h (55 mph)



(d) Trucks at 88 km/h (55 mph)



(e) Light vehicles at 112 km/h (70 mph)



(f) Trucks at 112 km/h (70 mph)

■ Passenger car ● SUV × Van ▲ Articulated truck ◆ Heavy truck

Figure 2– Effect of roughness on tire costs

4. Repair and Maintenance

4.1 Summary of findings

Two different approaches for estimating repair and maintenance (R&M) costs induced by pavement roughness were developed: (1) An empirical approach that introduced adjustment factors to update the tables reported in the 1982 TRDF study by Zaniewski et al., and (2) a mechanistic-empirical (M-E) approach that involves fatigue damage analysis using numerical modeling of vehicle vibration response. The results from the mechanistic-empirical approach were compared to the empirical results, and were found to be very close up to an IRI of 5 m/km (typical IRI range in the U.S), with a standard error of about 2% (Zaabar and Chatti, 2011). Figure 3 summarizes the R&M costs per km as a function of IRI for all vehicle classes and grade of 0%.

A computer program was also developed to facilitate the use of the model. The program can estimate repair and maintenance costs at the project and network levels. For project level analysis, the actual road profile should be used to account for the effect of roughness features.

4.2 Discussion

The results show that there is no effect of roughness up to IRI of 3 m/km. Beyond this range, an increase in IRI up to 4 m/km will increase R&M cost by 10% for passenger cars and heavy trucks. At IRI of 5 m/km, this increase is up to 40% for passenger cars and 50% for heavy trucks. Assuming that the average annual mileage for a passenger car is 24,000 km (15,000 miles), the repair and maintenance of the 255 million vehicles will cost about 244.8 billion dollars per year. Therefore, a decrease in IRI by 1 m/km (63.4 in/mile) will save 24.5 to 73.5 billion dollars per year in repair and maintenance cost.

As an example, if we consider the IRI distribution of the U.S. road network, about 14% of the roads have an IRI higher than 3m/km. Assuming that the average annual mileage for a passenger car is 24000 km (15,000 miles), and a total of 255 million cars travel on the US road network, the repair and maintenance cost for passenger cars in the U.S. can be estimated to be anywhere between 15 and 25 billion dollars per year (corresponding to vehicle speed ranging from 56 to 112 km/h, or 35 to 70 mph).

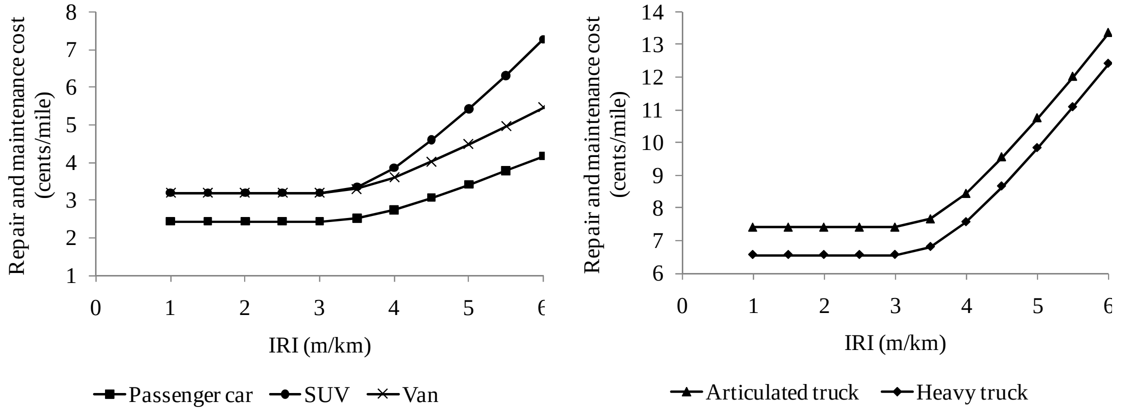
5. Effect of Pavement Conditions on Vehicle Operating Costs

5.1 Effect of roughness on VOC

The effect of pavement roughness (IRI) on VOC is estimated for all vehicle classes using the models developed in this study. Figures 2 through 4 show examples of fuel, tire and repair and maintenance costs expressed in cents (¢) per mile. Table 2 present examples of total cost expressed in cents (¢) per mile. The effect of roughness on VOC follows an exponential trend for all vehicle classes. The figures and the table were generated at 17˚C (62.6˚F, which is the average temperature in the U.S.), with mean profile depth of 1 mm (0.04 in) and grade of 0%.

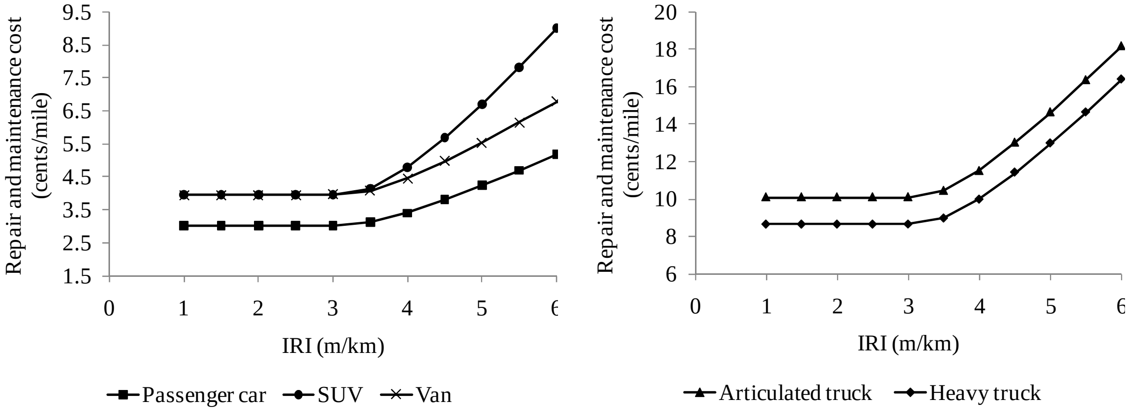
5.2 Effect of texture on VOC

The effect of pavement surface texture (MPD) on VOC is investigated for all vehicle classes using the models developed in this study. Table 3 presents examples of total cost expressed in cents (¢) per kilometer. The table was generated at 17˚C (62.6˚F), with IRI of 1 m/km (63.4 inch/mile) and grade of 0%.



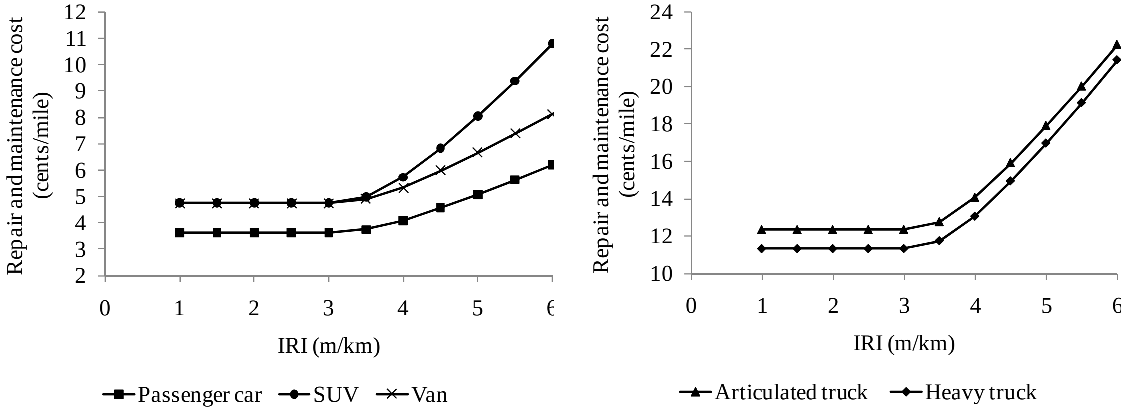
(a) Light vehicles at 56 km/h (35 mph)

(b) Trucks at 56 km/h (35 mph)



(c) Light vehicles at 88 km/h (55 mph)

(d) Trucks at 88 km/h (55 mph)



(e) Light vehicles at 112 km/h (70 mph)

(f) Trucks at 112 km/h (70 mph)

■ Passenger car ● SUV × Van ▲ Articulated truck ◆ Heavy truck

Figure 3– Effect of roughness on repair and maintenance costs

Table 2 – Effect of roughness on vehicle operating costs

Speed	Vehicle Class	Total Vehicle Operating Costs per Vehicle (¢/mile)										
		IRI (m/km)										
		1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6
56 (km/h) or 35 (mph)	Medium car	14.08	14.24	14.24	14.4	14.56	14.72	15.2	15.68	16.16	16.64	17.12
	Van	16	16.16	16.16	16.16	16.32	16.48	16.8	17.28	17.76	18.4	18.88
	SUV	16.32	16.48	16.48	16.64	16.8	17.12	17.76	18.72	19.68	20.64	21.76
	Light Truck	24	24.16	24.16	24.32	24.48	24.8	25.44	26.24	27.2	28.16	29.12
	Heavy Truck	46.08	46.56	46.88	47.36	47.68	48.32	49.44	50.88	52.48	54.08	55.84
	Arti. Truck	57.44	57.92	58.4	59.04	59.52	60.16	61.44	63.2	64.8	66.56	68.48
89 (km/h) or 55 (mph)	Medium car	16.8	16.96	17.12	17.28	17.44	17.6	18.08	18.72	19.2	19.84	20.48
	Van	20.16	20.16	20.32	20.32	20.48	20.64	21.12	21.6	22.24	23.04	23.68
	SUV	20.8	20.96	21.12	21.28	21.44	21.76	22.56	23.68	24.8	26.08	27.52
	Light Truck	34.88	35.04	35.2	35.2	35.36	35.68	36.64	37.76	39.04	40.32	41.76
	Heavy Truck	69.28	69.76	70.08	70.56	71.04	71.68	73.12	75.04	76.96	79.04	81.28
	Arti. Truck	90.4	90.88	91.52	92	92.64	93.44	95.2	97.28	99.36	101.8	104.2
112 (km/h) or 70 (mph)	Medium car	21.44	21.6	21.76	21.92	22.08	22.4	22.88	23.68	24.32	24.96	25.76
	Van	26.4	26.4	26.56	26.56	26.72	26.88	27.52	28.16	28.96	29.76	30.56
	SUV	28	28.16	28.48	28.64	28.8	29.28	30.24	31.52	32.96	34.56	36.16
	Light Truck	48.48	48.64	48.8	48.96	49.12	49.6	50.56	52	53.44	55.04	56.8
	Heavy Truck	97.76	98.24	98.72	99.2	99.68	100.64	102.4	104.64	107.2	109.92	112.64
	Arti. Truck	129.4	130.1	130.7	131.4	132	133.1	135.0	137.4	140.2	142.9	145.8

1 km = 0.62 mile; 1 mm = 0.039 in; 1 m/km = 63.4 in/mile; MPD=1 mm, Grade= 0%; Temperature = 17˚C (62.6˚F).

Table 3 – Effect of texture on vehicle operating costs

Speed	Vehicle Class	Total Vehicle Operating Cost per vehicle (¢/mile)										
		Mean Profile Depth (mm)										
		1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6
56 (km/h) or 35 (mph)	Medium car	14.08	14.08	14.08	14.08	14.08	14.24	14.24	14.24	14.24	14.24	14.24
	Van	16	16.16	16.16	16.16	16.32	16.32	16.48	16.48	16.48	16.64	16.64
	SUV	16.32	16.32	16.32	16.32	16.32	16.48	16.48	16.48	16.48	16.48	16.48
	Light Truck	24	24.16	24.16	24.32	24.48	24.64	24.64	24.8	24.96	25.12	25.12
	Heavy Truck	46.08	46.56	46.88	47.36	47.68	48	48.48	48.8	49.28	49.6	49.92
	Arti. Truck	57.44	57.92	58.4	59.04	59.52	60	60.48	60.96	61.44	61.92	62.4
89 (km/h) or 55 (mph)	Medium car	16.8	16.8	16.8	16.8	16.96	16.96	16.96	16.96	16.96	17.12	17.12
	Van	20.16	20.16	20.32	20.32	20.48	20.48	20.64	20.64	20.8	20.8	20.8
	SUV	20.8	20.8	20.8	20.8	20.96	20.96	20.96	20.96	20.96	21.12	21.12
	Light Truck	34.88	35.04	35.2	35.2	35.36	35.52	35.68	35.84	36	36.16	36.16
	Heavy Truck	69.28	69.76	70.08	70.56	71.04	71.36	71.84	72.32	72.64	73.12	73.6
	Arti. Truck	90.4	90.88	91.52	92	92.64	93.12	93.76	94.24	94.88	95.36	96
112 (km/h) or 70 (mph)	Medium car	21.44	21.44	21.44	21.44	21.44	21.6	21.6	21.6	21.6	21.76	21.76
	Van	26.4	26.4	26.56	26.56	26.72	26.72	26.88	26.88	27.04	27.04	27.2
	SUV	28	28	28.16	28.16	28.16	28.16	28.32	28.32	28.32	28.48	28.48
	Light Truck	48.48	48.64	48.8	48.96	49.12	49.28	49.44	49.6	49.76	49.92	50.08
	Heavy Truck	97.76	98.24	98.72	99.2	99.68	100.2	100.6	101.1	101.6	102.1	102.6
	Arti. Truck	129.4	130.1	130.7	131.4	132	132.6	133.3	133.9	134.6	135.2	135.8

1 km = 0.62 mile; 1 mm = 0.039 in; 1 m/km = 63.4 in/mile; IRI=1 m/km, Grade= 0%; Temperature = 17˚C (62.6˚F).

5.3 Discussion

The combined effect of MPD and IRI can be predicted by multiplying the roughness and texture factors. For example, if one would like to estimate the total VOC for IRI =3 m/km (190 in/mile) and MPD = 2 mm, for an articulated truck at 88 km/h (55 mph), divide 91.5 by 90.4 from Table 3, then multiply this ratio by 92.6. The cost obtained for these conditions is 94 cents/mile.

6. Case Study: Project level analysis

This section shows examples on how the VOC models can be used in practice. The unit costs are presented in Table 1. The software developed in this study was used to generate the results presented below. The VOC module is an engineering software application that allows one to calculate vehicle operating costs at the network and project levels. For network analysis, data for traffic, environmental and pavement conditions (IRI, MPD and pavement type) are the input to the module. For project analysis, one can import profiles in text format and the module will calculate the IRI. Entire analysis projects can be saved, which preserves user information and analysis inputs. After analyses have been performed, one can export a report of the results of any analyses.

6.1 Project level analysis

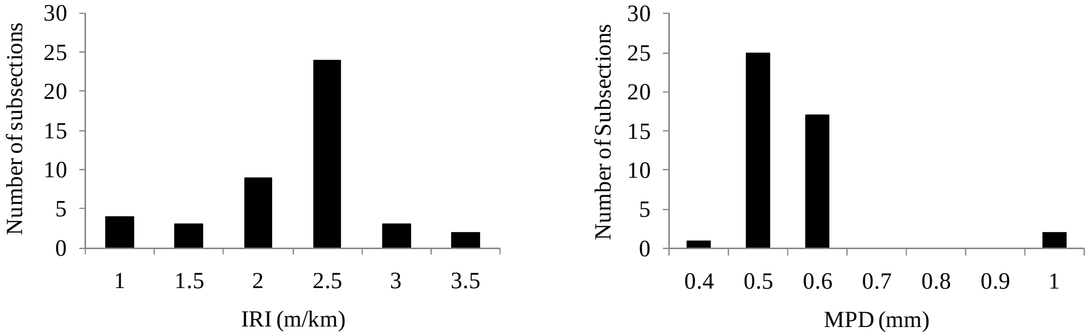
This example uses the mechanistic-based approach developed in this study to calculate the vehicle operating costs (fuel consumption, tire wear and repair and maintenance) for a 7.2 km (4.5 miles) long rigid pavement section on I-69 near Lansing, Michigan.

The Average Daily Traffic (ADT) for this section is 29,145 in both directions, with 60% passenger cars, 15% commercial trucks, 10% heavy trucks, 7% SUV, 4% vans, 2% light trucks, and 2% buses. The pavement condition data (raw profile and texture depth) were collected by the Michigan Department of Transportation using a Rapid Travel Profilometer and a Pavement Friction Tester. The grade was measured using a high precision GPS. Figure 4 summarizes the distributions of its pavement conditions.

The following procedure was followed to calculate VOC:

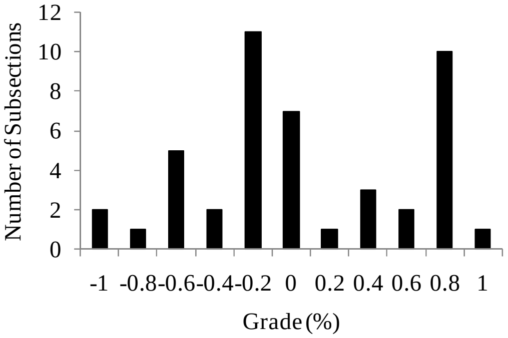
- For repair and maintenance costs, the profile was input to the computer program developed as part of this study. The software calculates the accumulated damage in the suspension system, which was translated into repair and maintenance costs.
- For fuel consumption and tire wear, the raw profile was divided into 0.16 km (0.1 mile) long subsections, and the IRI values were computed for each subsection. The other pavement conditions (grade, texture depth, and curvature) were input to the calibrated HDM 4 models to estimate fuel consumption and tire wear.
- The total costs were calculated according to the proportion of vehicle class mentioned above, and assuming average environmental conditions (Temperature = 17˚C (62.6˚F)).

Figure 5 shows the costs for each susbsection (0.16 km or 0.1 mile) for the traffic distribution generated at 96 km/h (60 mph) for trucks and buses and at 112 km/h (70 mph) for passenger cars, vans and SUVs. Each point represents a subsection. To estimate the reduction in VOC from rehabilitating the I-69 project, a raw profile of a newly overlayed pavement with an average IRI of 1 m/km (63.4 in/mile) was simulated. It was assumed that the grade and texture distribution were not affected by the rehabilitation.



1 m/km = 63.4 in/mile
(a) IRI Distribution

1 mm = 0.039 in
(b) Texture Distribution

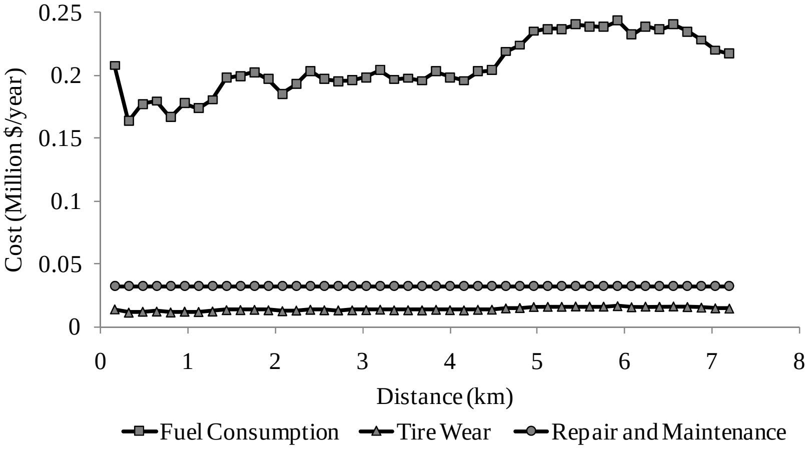


(c) Grade Distribution

Figure 4– Pavement conditions of the analysis section along I-69

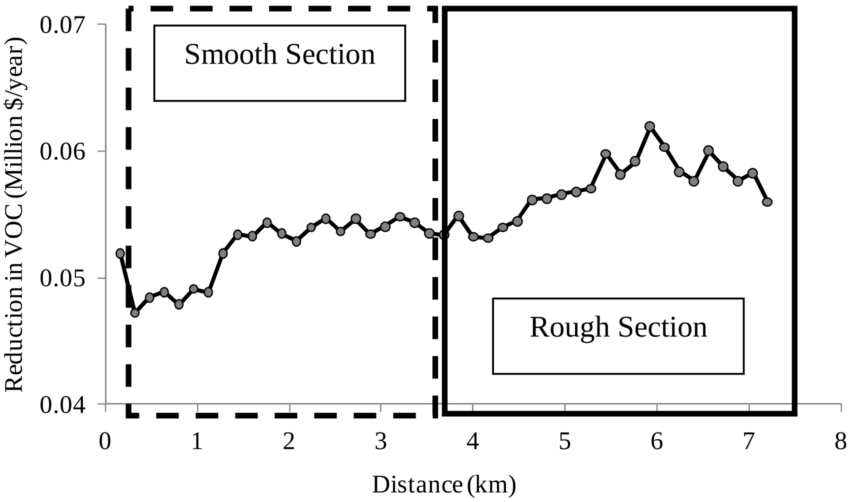
Figure 6 shows the reduction in VOC for each subsection. The total reduction in VOC from rehabilitating this project across 7.2 km (4.5 miles) will be about $2.46 Million per year.

These costs could be considered in a life cycle cost analysis (LCCA). This detailed analysis would help identify the segments of the pavement section that would result in higher operating costs. These segments would be considered for early maintenance.



1 subsection = 0.16 km; 1 km = 0.62 mile.

Figure 5– Costs per year induced along I-69 project by subsection



1 km = 0.62 mile

Figure 6– Reduction in VOC from rehabilitating each section of the I-69 project

7. Conclusion

The objective of this study was to investigate the effect of pavement conditions on Vehicle Operating Costs (VOC) including fuel consumption, tire wear and repair and maintenance. The research does not include the effect of pavement conditions on changes in travel time, nor does it consider the safety-related, environmental, or other implications of pavement conditions. The paper showed summary results and project level examples on how to use the calibrated VOC models in pavement management decisions. Some specific conclusions that were arrived at include:

- The most important cost components that are mostly affected by roughness are fuel consumption followed by repair and maintenance, then tire wear.
- Among pavement conditions (other than grade and curvature), the most important factors are surface roughness (IRI), followed by pavement type and surface texture (MPD), which play a secondary effect that is observed only for heavy trucks at low speed.

It is recommended to use the proposed calibrated models and the corresponding computer program to estimate vehicle operating costs at the project and network levels. For project level analysis, the actual road profile should be used to account for the effect of roughness features.

Finally, it should be noted that growing demand for fuel efficient vehicles accelerated the research and development (R&D) efforts to meet this demand. Therefore, new engine and combustion technologies, alternative fuels, vehicle design and maintenance, and tire technologies will affect vehicle operating costs in the future. This means that the recommended mechanistic-empirical models would have to be calibrated to address emerging technologies.

8. Acknowledgments

This research was conducted as part of the NCHRP project 1-45. The authors would like to acknowledge the financial support of the National Cooperative Highway Research Program (NCHRP) of the National Academies, the input of the technical panel and the TRB senior program manager, Dr. Amir Hanna. The authors also would like to thank the technical support from MDOT and Texas DOT for providing the repair and maintenance data of their fleet.

9. References

- Michigan Department of Transportation, "2009 Average Daily Traffic (ADT) Maps", http://www.michigan.gov/documents/lansing_19665_7.pdf, (Accessed November 2010).
- Zaabar, I., “Effect of Pavement Condition on Vehicle Operating Costs Including: Fuel Consumption, Vehicle Durability and Damage to Transported Goods”, Ph.D. Dissertation: Department of Civil and Environmental Engineering, Michigan State University, 2010.
- Zaabar, I. and Chatti, K., “Calibration of HDM4 Models for Estimating the Effect of Pavement Roughness on Fuel Consumption for U.S Conditions”, Transportation Research Record: Journal of the Transportation Research Board, 10-2132, pp 105-116, 2010.
- Zaabar, I. and Chatti, K., “A Field Investigation of the Effect of Pavement Type on Fuel Consumption”, Proceedings of the First T&DI Congress: Integrated Transportation and Development for a Better Tomorrow, 2011.
- Zaabar, I. and Chatti, K., “A New Mechanistic-Empirical Approach For Estimating The Effect Of Roughness On Vehicle Durability”, In Press, Transportation Research Record: Journal of the Transportation Research Board, 2011.
- Zaniewski, J. P., Butler, B. C., Cunningham, G., Elkins, G. E., Paggi, M. S., and Machemehl, R. (1982). "Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors." FHWA-PL-82-001, Texas Research and Development Foundation, Austin, Texas.